APPLICATION

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FOR

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ON

ALL-FIBER Q-SWITCHED LASER

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ALL-FIBER Q-SWITCHED LASER

BACKGROUND OF THE INVENTION

Field of the Invention

5   This invention relates to Q-switched lasers and more specifically to an all-fiber embodiment of a Q-switched laser.

Description of the Related Art

10   Q-switching is a widely used laser technique in which a laser pumping process is allowed to build up a much larger than usual population inversion inside a laser cavity, while keeping the cavity itself from oscillating by removing the cavity feedback or greatly increasing the cavity losses. 15 After a large inversion has been developed, the cavity feedback is restored to its usual large value, hence bringing the Q-factor to a high value, producing a very short, intense burst which dumps all the accumulated population inversion in a single short laser pulse. 20 Modulation of the cavity produces repetitive pulses. Lasers, Anthony E. Siegman, University Science Books, 1986, pp. 1004-1007.

As illustrated in figures 1a through 1d, the cavity loss 10 is initially set at some artificially high value – 25 that is, at an artificially low value of the laser cavity Q_c – while the inversion 12, hence the gain and the stored energy, in the laser medium are pumped up to a value much larger than normally present in the oscillating laser. The cavity loss is then suddenly lowered to a more normal value 30 (higher Q_c) so that the round-trip gain after switching is much larger than the cavity loss. The initial spontaneous emission or noise level in the laser cavity then immediately

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begins to build up at an unusually rapid rate, soon developing into a rapidly rising and intense burst, or "giant pulse" **14** of laser oscillation. The oscillation signal rapidly drives the inversion **12** down well below the new cavity loss level, after which the oscillation signal in the cavity dies out nearly as rapid as it rose. The peak power in the Q-switched pulse can be several orders of magnitude more intense than a cw laser created in the same laser with the same pumping rate.

Some of the more common Q-switching methods employed in practical laser system are shown in figures 2a through 2c. The laser cavity includes a gain medium **22** and a pair of mirrors **24** and **26**. As shown in figure 2a, mirror **26** is rotated (spinning motor shaft) so that the laser oscillated only during the brief interval when mirror **26** is aligned with mirror **24**. As shown in figure 2b, an electrooptic crystal **28** which becomes birefringent under the influence of applied voltage and one or more prisms **30** are placed inside the cavity. The birefringent crystal **28** rotates the polarization of the light energy so that it is coupled out of the cavity by the prism **30**. Electrooptic Q-switching provides fast switching with precise timing and good stability but the repeat rate is relatively slow and the crystal and pulse source are fairly expensive, as the voltage needed to switch one polarization to the other is more than a few hundred volts. As shown in figure 3c, an rf acoustic wave created in the optical material **32** at the Bragg condition diffracts light out of the cavity to lower the Q. Acoustic modulators have a fast repeat rate but are expensive and a slower switch speed as well as limited aperture size.

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There remains a need for an inexpensive and reliable Q-switched laser that provides for narrow pulse widths and fast repeat rates.

5   SUMMARY OF THE INVENTION

The present invention provides an inexpensive all-fiber Q-switched laser with narrow pulse widths and fast repeat rates.

This is accomplished with a fiber chain in which a gain
10   medium is provided between narrow and broadband fiber gratings that define a polarization-dependent resonant cavity. A pump source couples energy into the fiber chain to pump the gain medium. A modulator applies stress to the fiber chain to induce birefringence and switch the cavity Q-
15   factor to alternately store energy in the gain fiber and then release the energy in a laser pulse.

In one embodiment, the narrowband fiber grating is formed in a polarization maintaining (PM) fiber creating two reflection bands that correspond to different polarization
20   modes. The broadband grating has a reflection band that is aligned to one of the PM fiber's reflection bands so that the normal Q-factor is high. The application of stress to the fiber chain changes the polarization of light oscillating in the fiber chain to reduce the Q-factor and
25   store energy in the gain fiber. Removal of the stress returns the birefringence, hence polarization to its initial state thereby increasing the Q-factor and quickly releasing the energy in a laser pulse.

In another embodiment, some portion of the fiber chain
30   comprises a polarization-dependent fiber whose transmission depends on the polarization of the oscillating light energy. Stress induced birefringence of the fiber chain switches

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the Q-factor to store energy and then release energy in a laser pulse.

In another embodiment, the fiber gratings are formed in passive silica fiber and fusion spliced to an active oxide-based multi-component glass fiber. Multi-component glasses support higher concentrations of rare-earth dopants and thus higher output power or single-frequency output.

These and other features and advantages of the invention will be apparent to those skilled in the art from the following detailed description of preferred embodiments, taken together with the accompanying drawings, in which:

BRIEF DESCRIPTION OF THE DRAWINGS

FIGs. 1a-1d, as described above, is a schematic illustrating the fundamental dynamics of laser Q-switching;

FIGs. 2a-2c, as described above, are known Q-switched lasers;

FIG. 3 is an all-fiber embodiment of a stress-induced birefringent Q-switched laser in accordance with the present invention;

FIGs. 4a and 4b illustrate polarization dependence and stress-induced birefringence;

FIG. 5 is another all-fiber embodiment of a stress-induced birefringent Q-switched laser;

FIG. 6 is a plot of reflectivity versus wavelength for a narrowband grating formed in a polarization maintaining fiber;

FIGs. 7a and 7b are diagrams illustrating a non-birefringent cavity;

FIGs. 8a and 8b are diagrams illustrating a birefringent cavity;

FIG. 9 illustrates the polarization-dependent

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reflectivity of the narrowband grating to circular or 45 degree polarized light for an alternate embodiment of stress-induced birefringence; and

FIG. 10 is a plot of Q-switched laser pulses generated
5   by the all-fiber Q-switched laser.

DETAILED DESCRIPTION OF THE INVENTION

Stress-induced birefringence of an all-fiber polarization-dependent resonant cavity provides an
10 inexpensive Q-switched laser with narrow pulse widths, high repetition rates and peak powers.   In general, the pulse width is less than 100 ns, the repetition rate is greater than 1 kHz and the peak power is greater than 1 W.

As shown in figure 3, an all-fiber Q-switched laser **40**
15 includes a fiber chain **42** held in a mounting fixture **44**. The fiber chain includes a gain medium **46** formed between narrow and broadband fiber gratings **48** and **50** that define a polarization-dependent resonant cavity. A pump source **52** such as a single or multi-mode laser diode couples energy **54**
20 into fiber chain **42** to pump gain medium **46**. A modulator **56** applies mechanical stress to a portion of the fiber chain to affect its birefringence and change the cavity Q-factor. Typically, in the normal or unstressed state, the cavity losses are low (high Q) to sustain lasing.   Thus, the
25 stress-induced birefringence lowers the Q so that cavity losses exceed gain and the pump energy is stored in the gain medium.   When the stress is removed, the Q returns to its normal high value and the cavity releases the energy in a laser pulse **58**.   Alternately, the cavity could be configured
30 so that the stress-induced state corresponds to a high Q factor.

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The polarization dependence of the resonant cavity and the stress-induced birefringence are illustrated in figures 4a and 4b. Polarization dependence is created by either forming at least a portion of the fiber chain with a fiber whose transmission properties are polarization dependent or forming the narrowband grating on a polarization maintaining fiber (see figure 5).

Figure 4a is a plot **60** of the transmission (reflectance) versus polarization state of the light at the wavelength where the gratings are aligned to lase. For purposes of explanation only, we assume that the light in the cavity is ordinarily linearly polarized with a vertical or "V-polarization" and the cavity is configured to have a high transmission (reflectance) **62** for V-polarized light at the laser wavelength. In the ordinary unstressed state, the cavity losses are low and the cavity would sustain laser oscillation. When the retardance having the optical axis 45 deg. with respect to V/H, vertical or horizontal, of the stress induced birefringence is quarter-wave or $\pi/2$, the light is rotated to a horizontal or "H-polarization" at which the transmission (reflectance) **64** is below the threshold **66** needed to sustain laser oscillation. The birefringence need only be sufficient to shift the polarization to a point on the curve below the threshold. The combination of stress-induced birefringence with a polarization-dependent cavity provides an efficient Q-switched laser.

Figure 4b illustrates the concept of stress-induced birefringence. A material that displays two difference indices of refraction n_x and n_y is said to be birefringent. It is well known that the application of mechanical stress

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to an isotropic material (same refractive index in all directions) will change the refractive indices and induce birefringence. For example, an isotropic material **70** such as an optical fiber has indices of refraction n_x and n_y of

5   equal value. V-polarized light traveling through this isotropic material will be retarded by an equal amount in all directions and its polarization will be unaffected. However, the application of stress to the fiber will, for example, reduce refractive index n_y and induce birefringence,

10   when the direction of polarization is not the direction of one of the optical axis of birefringence. The same light propagating through the now birefringent material will be retarded by different amounts affecting the polarization. In the example given above, if the induced birefringence is

15   quarter-wave a double-pass through the material will change V-polarized light to H-polarized light, if the axis of birefringence, which is a function of the orientation of the stress, is 45 deg. to the vertical/horizontal.

As shown in figure 5, an all-fiber Q-switched laser **80**

20   includes a fiber chain **82** held in a mounting fixture **84**. The fiber chain includes a gain fiber **86** spliced between a narrowband fiber grating **88** fabricated in a polarization maintaining (PM) fiber **90** and a broadband fiber grating **92** fabricated in a fiber **94** (may or may not be PM fiber). As

25   shown in figure 6, the narrowband grating, provided it is sufficiently narrow, e.g. 0.05 nm for 1um laser wavelength, resolves two reflection bands **96** and **98** that correspond to different polarization modes, e.g. V and H polarization. The broadband grating reflection band **100** overlaps, and is

30   preferably aligned with, one of the two reflection bands, shown here as band **96**, to define a polarization dependent

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cavity with a high Q factor for light at the laser wavelength λ_0 and the correct polarization. A pump source 102 couples energy 104 into fiber chain 82 to pump gain fiber 86.

5   A piezoelectric transducer (PZT) 106 is mounted on an exposed portion of fiber chain 82 and in response to an external signal from signal source 108 applies mechanical stress to the fiber chain to affect its birefringence and change the cavity Q-factor to generate a giant pulse 109.
10 The PZT is a simple, low cost device that can be mounted on the fiber chain in a compact package. The PZT operates at less than 50V, which is very important for purposes of safety qualification, has a fast response time and is capable of fast repetitions.

15   The stress-induced birefringence of an all-fiber polarization-dependent resonant cavity can be quantitatively analyzed in the following Jones-Matrix analysis. The round-trip Jones-Matrix RT can be written as

$$RT = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} [\Omega] \begin{pmatrix} e^{i\frac{\phi}{2}} & 0 \\ 0 & e^{-i\frac{\phi}{2}} \end{pmatrix} [\Omega]^{-1} \begin{pmatrix} R & 0 \\ 0 & 0 \end{pmatrix} [\Omega] \begin{pmatrix} e^{i\frac{\phi}{2}} & 0 \\ 0 & e^{-i\frac{\phi}{2}} \end{pmatrix} [\Omega]^{-1}$$

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$$[\Omega] = \begin{pmatrix} \cos\Omega & -\sin\Omega \\ \sin\Omega & \cos\Omega \end{pmatrix}$$

where Ω, ϕ, and R represent the angle between the stress-birefringence and the axis of the PM fiber 90, the amount of birefringence, and the reflectivity of the narrowband
25 grating 88. The reflectivity of the non-PM FBG 92 is assumed to be 1 for both polarizations, and the reflectivity of the narrowband grating at the other (nonoperating)

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polarization is stipulated to zero, as it is for any wavelength within the entire reflection band of the broadband FBG. The eigenvalues of the Jones-Matrix RT are 0 and $R(\cos\phi + i\sin\phi\cos 2\Omega)$, each representing the cold-cavity "gain" (i.e., 1-$loss$) for the nonoperational polarization and the operational polarization, respectively. One of the eigenvalues is zero, indicating the resonator supports only one polarization mode. The other (non-zero) eigenvalue indicates the gain/loss of the cavity. The eigenvalue can be a complex number as it represents the field quantity. The round-trip loss of the cavity depends on the amount of birefringence, which can be changed by applying a waveform to the PZT. The round-trip loss also depends on the orientation of the stress with respect to the PM axis, which must be pre-aligned. In an extreme example, when the stress birefringence is oriented 45° to the axis of the PM fiber and the retardance is 90° (quarter-wave), the cavity is completely suppressed, as the operational polarization will be switched to the other polarization state after one round-trip. By changing the cavity loss rapidly, effective Q-switching will be accomplished by a very simple configuration.

As shown in figures 7a and 7b, without stress being applied to the fiber chain, the material **110** remains isotropic, i.e. n_x and n_y are the same. Light propagates in the cavity from the narrowband fiber grating **98** at one end (1) through the fiber chain (2) reflects off the broadband grating **92** (3) back through the fiber chain (4) and to the narrowband grating **98** (5) and retains its original polarization, shown here as a V-polarization **112**. As a result, the reflection band **96** for V-polarized light is

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aligned to the broadband reflection band **100**. This defines a low loss high Q cavity capable of sustaining laser oscillation.

As shown in figures 8a and 8b, the application of
5   stress to the fiber chain makes the material **110** birefringent, i.e. n_x and n_y are different. Vertically polarized light **112** propagates in the cavity from the narrowband fiber grating **98** at one end (1) through the birefringent material (2), which retards the light by a
10   quarter-wave thereby circularly polarizing the light. The circularly polarized light reflects off the broadband grating **92** (3) back through the fiber chain (4) and the birefringent material, which retards the light by another quarter-wave giving it a horizontal-polarization at the
15   narrowband grating **98** (5). As a result, the H-polarized light sees little to no reflection at the laser wavelength, which defines a high loss low Q cavity incapable of sustaining laser oscillation. The reflection band **98** for H-polarized light lies at a wavelength outside the broadband
20   reflection band.

As shown in figure 9, the amount of retardance introduced by the birefringence need not be quarter-wave. The retardance need only reduce the effective reflectance/transmission of the cavity enough that the
25   cavity losses exceed the cavity gain. In this case, the round-tip retardance produces a polarization having both V and H components at the laser wavelength. However, as shown only the v-polarized reflection band **120** overlaps the broadband reflection band **122** at the laser wavelength. The
30   H-polarized reflection band **124** lies at a different wavelength outside reflection band **122**. As a result, only

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the V-polarized component is reflected. Thus, the effective reflectance is reduced below the cavity threshold.

Stress-induced birefringence of an all-fiber polarization-dependent resonant cavity defines a new architecture for a Q-switched laser. The all-fiber Q-switched laser can be configured with a variety of glasses, dopants, fibers and gratings to output laser pulses and sequences of pulses at different wavelengths, power levels, mode structures (single and multimode), pulse widths and repetition rates. Referring to figure 5, in one embodiment gain fiber **86** is formed of an oxide-based multi-component glass such as phosphate, germanate or tellurite and doped with one or more rare-earth elements (Er, Yb, Nd, Tm, Ho). Multi-component glasses support higher concentrations of rare-earth dopants, e.g. 0.5 to 30 wt. % without quenching or clustering, orders of magnitude higher than conventional silica glasses. These glasses support both higher output powers and shorter cavity lengths needed for single-frequency operation.   However, current multi-component glasses are not photosensitive and relatively fragile. Thus, the PM fiber **90** and fiber **94** are suitably formed from passive silica glass and fusion spliced to the gain fiber. A suitable process for fusion splicing thermally dissimilar fiber is described in co-pending U.S. application Serial No. 10/374,001 entitled "Method of Angle Fusion Splicing Silica Fiber with Low-Temperature Non-Silica Fiber" filed on February 25, 2003 the entire contents of which are incorporated by reference.

The all-fiber Q-switched laser was tested with a 2 cm length of gain fiber of phosphate glass doped with 2 wt. % of Er and 2 wt.% of Yb. The gratings were formed in passive silica fiber at a wavelength of 1.55 microns.   The

narrowband and broadband gratings had a precision $\Delta\lambda$ = 0.05nm and 0.3nm, respectively. The fiber chain was pumped with a 390 mW single-mode pump. As shown in figure 10, the PZT was modulated at 100 kHz and generates pulses **130** that stress the fiber. The Q-switched laser generated a sequence of pulses **128** with a FWHM of 15 ns, a peak power of 15 W.

While several illustrative embodiments of the invention have been shown and described, numerous variations and alternate embodiments will occur to those skilled in the art. Such variations and alternate embodiments are contemplated, and can be made without departing from the spirit and scope of the invention as defined in the appended claims.